

Driving Weiss oscillations to Zero Resistance States by Microwave Radiation

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In this work we present a theoretical model to study the effect of microwave radiation on Weiss oscillations. In our proposal Weiss oscillations, produced by an spatial periodic potential, are modulated by microwave radiation due to an interference effect between both, space and time-dependent, potentials. The final magnetoresistance depends mainly on the spatial period of the spatial potential and the frequency of radiation. Depending on the values of these parameters, we predict that Weiss oscillations can reach zero resistance states. On the other hand, these dissipationless transport states, created just by radiation, can be destroyed by the additional presence of a periodic space-dependent potential. Then by tuning the spatial period or the radiation frequency, the magnetoresistance can be strongly modified.

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In the last two decades a lot of progress has been made in the study of two-dimensional electron systems (2DES), and very important and unusual properties have been discovered when these systems are subjected to external potentials. Nowadays magnetotransport properties of highly mobile 2DES are a subject of increasing interest. In particular the study of the effects that radiation can produce on these nano-devices is attracting considerable attention both from theoretical and experimental sides¹. On the other hand, the interplay of two different periodic modulations in a physical system will bring to interesting features in dynamics and transport. For instance, the study of the effect of microwave (MW) radiation on 2DES transport properties such as Weiss oscillations^{2,3} represents a topic that deserves to be studied^{4,5}. Especially if we consider that MW radiation gives rise also to magnetoresistance (ρ_{xx}) oscillations in 2DES and, at high MW intensity, zero resistance states (ZRS)^{6,7,8,9}. Weiss oscillations are also a type of ρ_{xx} oscillations observed in high mobility 2DES with a lateral periodic modulation (superlattice) imposed in one direction. In this proposed scenario electrons are subjected simultaneously to two different periodic potentials. One is space-dependent, i.e., the superlattice, and the other is time-dependent, i.e., MW radiation. Thus, interesting properties can be expected due to the combined effect of both potentials.

In this letter we present firstly a theoretical approach to treat Weiss oscillations. Secondly we introduce a more general model to consider at the same footing the effects of a spatial periodic modulation and MW radiation on the transport properties of a 2DES. The former model is an alternative to the ones presented to date to investigate Weiss oscillations. In these models^{2,3,10} Weiss oscillations are explained in terms of an oscillatory dependence of the bandwidth of the modulation-broadened Landau levels of the 2DES. Beenakker presented a model which considers a semiclassical approach¹¹. In this case the effect is explained as a resonance effect between the orbit motion and an oscillating drift produced by magnetic field and the electric field imposed by the unidirectional

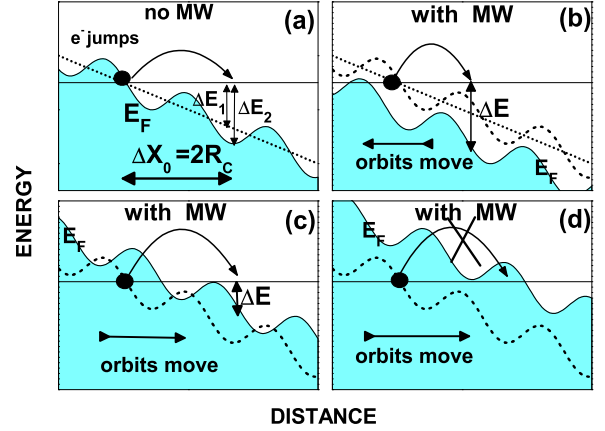


FIG. 1: Schematic diagrams of electronic transport of a 2DES with a spatial periodic modulation in one direction. Thus, the Fermi energy presents a periodic and tilted modulation in the transport direction. In Fig.(1.a) no MW field is present. Compared to the case without superlattice (ΔE_1), more or less energy can be dissipated depending on the modulated Fermi energy (ΔE_2). When the MW field is on, the orbits oscillate with w . In Fig.(1.b) the orbits move backwards during the jump. In Fig.(1.c) the orbits are moving forwards but still the electronic jump can take place. In Fig. (1.d) the orbits are moving forwards but for a higher MW intensity, the combined effects of spatial modulation and MW radiation make their amplitudes larger than the electronic jump. Thus the electron movement between orbits cannot take place because the final state is occupied. This situation corresponds to ZRS.

periodic potential. In the proposal presented here the origin of Weiss oscillations is a periodically modulated Fermi energy as a direct consequence of the spatial periodic potential $V(x)$ imposed on the 2DES. The spatially modulated Fermi energy changes dramatically the scattering conditions between electrons and charged impurities presented in the sample. Depending on the external

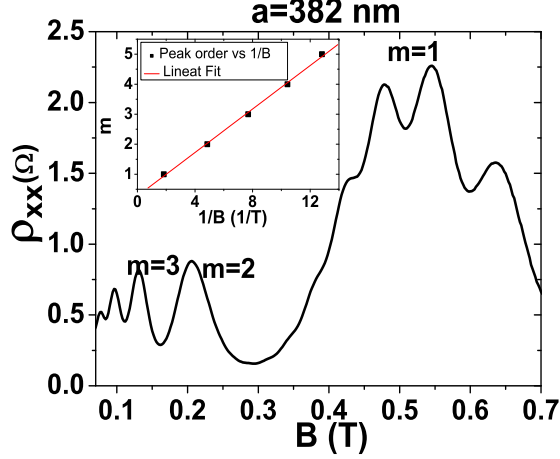


FIG. 2: Calculated ρ_{xx} as a function of magnetic field B (Weiss oscillations). The period of the static modulation is $a = 382\text{nm}$ and the modulation amplitude is $V_0 \sim 0.1\text{meV}$. The inset shows the linear dependence of the peak index m vs $1/B$ which means that Weiss oscillations are periodic in $1/B$. $T=1\text{K}$.

DC magnetic field (B), compared to the case without superlattice modulation, at certain B the transport will be more dissipative. This corresponds to a peak in ρ_{xx} . Meanwhile in others, the transport will be less dissipative corresponding to a ρ_{xx} valley. Under this scenario it is expected that the presence of MW radiation¹² will alter dramatically the ρ_{xx} response of the system. We predict that the combined effect of MW radiation and spatial potential will lead the system to a interference regime with constructive and destructive responses. As a consequence ρ_{xx} will present a modulated profile and for a sort of external parameters, spatial modulation and MW frequency (w), ZRS can be created or destroyed. The theory presented here can have potential applications in other fields and systems like nano electro-mechanical systems (NEMS)¹³ with AC-potentials and surfaces acoustic waves (SAW)¹⁴ in 2DES or dots illuminated with MW radiation. In other words, the physics presented in this letter can be of interest, from a basic physics standpoint, for an audience dealing with the effects that AC or/and DC fields produce on nano-devices.

Our system consists in a 2DES subjected to a perpendicular B (z-direction) and a DC electric field (E_{dc}) (x-direction). We include the unidirectional periodic potential $V(x) = V_0 \cos Kx$ where $K = 2\pi/a$, a being the spatial period of the superlattice. The total hamiltonian H , can be written as:

$$H = \frac{P_x^2}{2m^*} + \frac{1}{2}m^*w_c^2(x - X_0)^2 - eE_{dc}X_0 + \frac{1}{2}m^*\frac{E_{dc}^2}{B^2} + V_0 \cos(Kx) = H_0 + V_0 \cos(Kx) \quad (1)$$

X_0 is the center of the orbit for the electron spiral motion: $X_0 = \frac{\hbar k_y}{eB} - \frac{eE_{dc}}{m^*w_c^2}$, e is the electron charge, w_c is the cyclotron frequency. H_0 is the hamiltonian of a harmonic quantum oscillator and its wave functions, the well-known oscillator functions (hermite polynomials). We treat $V_0 \cos(Kx)$ in first order perturbation theory and the first order energy correction is given by: $\epsilon_n^{(1)} = V_0 \cos(KX_0)e^{-X/2}L_n(X) = U_n \cos(KX_0)$, where $X = \frac{1}{2}l^2K^2$, $L_n(X)$ is a Laguerre polynomial and l the characteristic magnetic length. Therefore the total energy for the Landau level n is given by: $\epsilon_n = \hbar w_c(n + \frac{1}{2}) - eE_{dc}X_0 + U_n \cos(KX_0)$. This result affects dramatically the Fermi energy as a function of distance (see Fig. 1), showing now a periodic, tilted modulation.

Now we introduce impurity scattering suffered by the electrons in our model^{9,12,15}. When one electron scatters elastically due to charged impurities, its average orbit center position changes, in the electric field direction, from X_0 to X'_0 . Accordingly the average advanced distance in the x direction is given by $\Delta X_0 = X'_0 - X_0 \simeq 2R_c$, $R_c = \frac{\sqrt{2m^*E_F}}{eB}$ being the orbit radius (see Fig. 1). Without the static periodic modulation $V(x)$, this distance corresponds to an energy increase regarding the Fermi energy given by $\Delta\epsilon = \epsilon_n - \epsilon_{n'} \simeq eE_{dc}2R_c$. This energy is eventually dissipated by the lattice being responsible of the magnetoresistance measured in the sample. Thus, there is a direct relation between advanced distance and dissipated energy. However if the 2DES is subjected to $V(x)$, the energy increase has a different expression:

$$\Delta\epsilon \simeq eE_{dc}2R_c + U_n[\cos(KX_0) - \cos(KX'_0)] \quad (2)$$

To evaluate the *average energy change* in the scattering jump, we consider that for the initial position, X_0 , the electron has the same energy as without $V(x)$ (see Fig 1a). Thus, the net energy change in the jump comes only from the final position X'_0 . This implies that $\cos KX_0 = 0 \Rightarrow KX_0 = (2m+1)\pi/2$ with $m = 0, 1, 2, 3, \dots$. Taking for simplicity the case $m = 0$, $\Rightarrow KX'_0 = 2R_cK + \pi/2$, and considering the asymptotic relation for $L_n(X)$ ¹⁶ (for large values of n), $L_n(X) \rightarrow J_0(2\sqrt{X})$ we can finally write for $\Delta\epsilon$:

$$\Delta\epsilon \simeq eE_{dc}2R_c - V_0e^{-X/2}J_0(2\sqrt{X})\cos\left[2\left(R_cK + \frac{\pi}{4}\right)\right] \quad (3)$$

being J_0 Bessel function of zero order. According to this expression the energy difference regarding the Fermi energy is now depending of $\frac{1}{B}$ through a cosine function. Thus, it can be larger or smaller than the situation without static modulation (see Fig. 1a). A larger or smaller energy is now dissipated giving rise to an increasing or decreasing ρ_{xx} , i.e., ρ_{xx} oscillations. The advanced distance corresponding to $\Delta\epsilon$ can be calculated straightforward:

$$\Delta X_T = 2R_c - \frac{V_0e^{-X/2}J_0(2\sqrt{X})}{eE_{dc}}\cos\left[2\left(R_cK + \frac{\pi}{4}\right)\right] \quad (4)$$

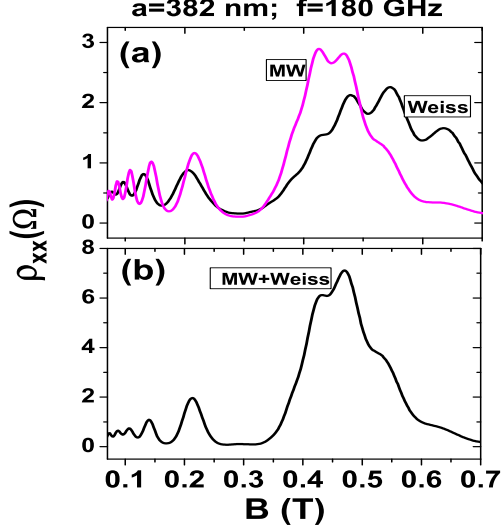


FIG. 3: Calculated ρ_{xx} vs B . In Fig. 3a, the Weiss-labeled curve corresponds to the 2DES with an spatial periodic potential (same parameters as Fig. 2) imposed on top of it, but not illuminated with MW. The MW-labeled curve corresponds to the same 2DES without spatial periodic potential but being illuminated with MW. None of them present ZRS. In Fig. 3b, the sample is subjected to both potentials and ZRS are obtained around $B = 0.3T$. ($T=1K$.)

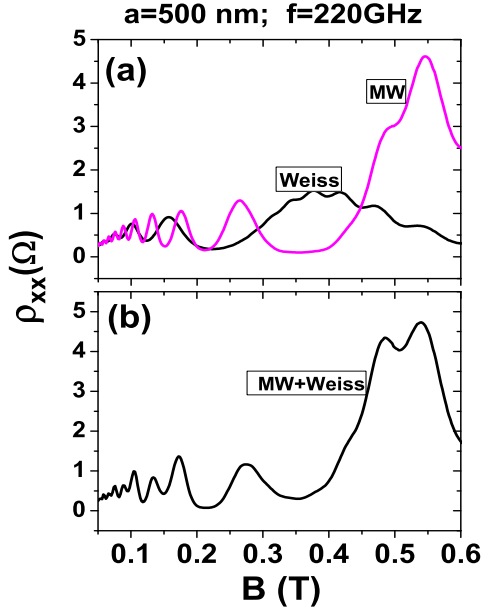


FIG. 4: Calculated ρ_{xx} vs B . Similar panels as in Fig. 3. We observe creation ($B = 0.2T$) and destruction ($B = 0.35T$) of ZRS due to the combined effect of both periodic potentials. ($T=1K$).

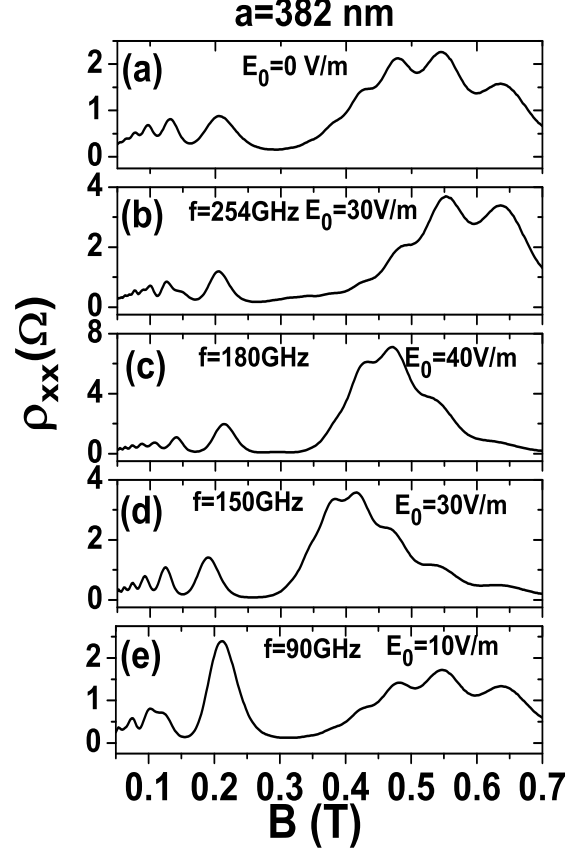


FIG. 5: Calculated ρ_{xx} vs B for a 2DES with a spatial periodic potential (same parameters as in Fig. 2) under different regimes. In Fig. 5a there is no MW field. From Fig. 5b to 5e we present calculated results with the MW field on and for four different frequencies. ($T=1K$.)

Following references [9,12,15] from ΔX_T we calculate a drift velocity for the electron dissipative transport in the x direction and finally we obtain ρ_{xx} . According to this expression the minima values of ρ_{xx} are obtained for $2R_c = [m - \frac{1}{4}]a$, (commensurability condition)². The maxima for $2R_c = [m + \frac{1}{4}]a$. In Fig. 2 we represent calculated ρ_{xx} as a function of B . The period of the static modulation is $a = 382$ nm and the modulation amplitude is $V_0 \sim 0.1meV$. The substructure appearing at higher B corresponds to the Shubnikov-deHaas oscillations. We reproduce Weiss oscillations with reasonable agreement with experiments^{2,3}.

If now we switch on the MW field, we expect that its effect will alter dramatically the ρ_{xx} response of the system. From the MW driven Larmor orbits model^{9,12} radiation forces the electronic orbits to move back and forth at the frequency of the field. This affects the scattering conditions of the 2DES increasing or decreasing the distance of the scattering jump giving rise to MW-

induced ρ_{xx} oscillations. Both effects, periodic spatial modulation and MW radiation alter simultaneously the average advanced distance when the electron scatters (see Fig. 1). We obtain an expression for the total average distance in the x direction:

$$\Delta X_T = 2R_c - S \cos \left[2 \left(R_c K + \frac{\pi}{4} \right) \right] + A \cos(w\tau) \quad (5)$$

where $S = \frac{V_0 e^{-X/2} J_0(2\sqrt{X})}{eE_{dc}}$ and $A = \frac{eE_0}{m^* \sqrt{(w_c^2 - w^2)^2 + \gamma^4}}$. E_0 is the MW electric field amplitude, γ is a phenomenologically introduced⁹ damping parameter and τ the scattering time. As in the previous case without MW, from ΔX_T we calculate an electron drift velocity^{9,12,15} and finally ρ_{xx} of the system. According to our model there is a direct relationship between ΔX_T and ρ_{xx} :

$$\rho_{xx} \propto -S \cos \left[2 \left(R_c K + \frac{\pi}{4} \right) \right] + A \cos(w\tau) \quad (6)$$

Therefore from equation 6 we can predict an interference regime between both periodic potentials which will be reflected on ρ_{xx} ¹⁷. That means that depending mainly on a , w and for some values of B , ρ_{xx} will present a constructive response and a reinforced signal. Accordingly ZRS can be found where they did not exist before. Also we can have in some points much higher current than the dark case. For other values of B the interference will be destructive and the ρ_{xx} response will be closer to the one of the dark case. Also the destructive interference can get rid of ZRS that MW radiation can previously create. In other words, ZRS created by the action of MW radiation on a 2DES can be destroyed by the additional presence of a spatial periodic potential on the system.

In Fig. 3a we present calculated ρ_{xx} vs B for two different regimes of the same 2DES. In one (Weiss-labeled) the system has a superlattice (parameters of Fig. 2) imposed

in the transport directions but it is not illuminated with MW. We obtain the well-known Weiss oscillations. In the other (MW-labeled) the system does not present the superlattice but it is illuminated with MW. We obtain the also well-known MW-induced resistance oscillations. In none of them ZRS show up. In Fig. 3b we present calculated ρ_{xx} vs B showing the combined effect of both potentials. We can see clearly that ZRS show up around $B = 0.3T$. In Fig. 4 we present similar panels as in Fig. 3 but for different a and w . We observe in the bottom panel two opposite effects in terms of ZRS: the combined effect of both periodic potentials are able to create ZRS where they did not exist before (around 0.2 T) or destroy them where they existed (around 0.35 T). In Fig. 5 we can see calculated ρ_{xx} vs B for a 2DES with a spatial periodic potential of $a = 382$ nm, under different regimes. In Fig. 5a we present same results as in Fig. 2 just for comparison. From Fig. 5b to 5e we present calculated results with the MW field on and for four different frequencies. Comparing the bottom panels to the top one we can see the different interference effects.

In summary, we have analyzed the interplay between a spatially modulated periodic potential and a time-dependent periodic field and its effect on the magnetotransport in a 2DES. In particular, we have presented a theoretical approach to investigate the effect of microwave radiation on Weiss oscillations. In our proposal Weiss oscillations are modulated by microwave radiation due to an interference effect between both, spatial and time-dependent, periodic potentials. The final profile presented by ρ_{xx} depends mainly on the spatial period of the superlattice modulation and the frequency of MW.

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